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Central Compact Objects in Supernova Remnants

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Abstract. There are point-like sources in central regions of several supernova remnants which have not been detected outside the X-ray range. The X-ray spectra of these Central Compact Objects (CCOs) have thermal components with blackbody temperatures of 0.2–0.5 keV and characteristic sizes of 0.3–3 km. Most likely, the CCOs are neutron stars born in supernova explosions. We overview their observational properties, emphasizing the *Chandra* data, and compare them with magnetars.

1. Introduction

X-ray observations have shown a new population of radio-quiet compact objects, presumably isolated neutron stars (INSs), apparently different from both isolated rotation-powered pulsars and accretion-powered X-ray pulsars in close binary systems. About 10 of these objects (AXPs and SGRs), which show pulsations with periods in a 5–12 s range, large period derivatives, $\dot{P} \sim 10^{-12}$–10^{-10}, and/or strong bursts are believed to be *magnetars* (Thompson & Duncan 1996), i.e., INSs with superstrong magnetic fields, $B \sim 10^{14}$–10^{15} G. The magnetars in quiescence have typical X-ray luminosities 10^{34}–10^{35} erg s^{-1} and show two-component spectra, a thermal component with a blackbody (BB) temperature of 0.4–0.7 keV and a non-thermal component described by a power-law (PL) with a photon index around 3. At least two magnetars have associated supernova remnants (SNRs). The second class of radio-quiet INSs includes colder (apparently older) nearby objects, showing soft thermal spectra with temperatures in a 50–150 eV range and luminosities $\sim 10^{32}$–10^{33} erg s^{-1}. At least some of these objects, sometimes dubbed *Dim Isolated Neutron Stars*, are likely ordinary rotation-powered pulsars whose radio beams are not observable from Earth. Third is a class of point-like X-ray sources found near the centers of SNRs that cannot be identified as active radio pulsars or magnetars. These *Central Compact Objects* (CCOs), presumably INSs, have thermal spectra with BB temperatures 0.2–0.5 keV and X-ray luminosities $L_{\rm x} \sim 10^{33}$–10^{34} erg s^{-1}. We define a CCO as an X-ray point source which (1) is found near the center of a SNR, (2) shows no radio/γ-ray counterpart, (3) shows no pulsar wind nebula (PWN), (4) has a soft thermal-like spectrum. Current observational status of CCOs is discussed below.

2. Classification and General Observational Properties

In the previous review by Pavlov et al. (2002a; P02 hereafter), five CCOs were discussed. Since then three additional CCO candidates have been suggested

(Seward et al. 2003; Lazendic et al. 2003; Koptsevich et al. 2003). Table 1 provides a list of the eight objects (the new ones marked with 'n'), their associated SNRs, the age and distance to the SNR, the period, and the X-ray flux (in units of 10^{-12} erg cm^{-2} s^{-1}, for a range of 0.4–8 keV). We believe that two of these objects, marked with 'x' in Table 1, do *not* actually belong to the CCO class because of their distinctive properties, as discussed below.

Object	SNR	Age kyr	d kpc	P	$F_{\mathrm{x},-12}$
J232327.9+584843	Cas A	0.32	3.3–3.7	...	0.8
J085201.4−461753	G266.1−1.2	1–3	1–2	...	1.4
J161736.3−510225(x)	RCW 103	1–3	3–7	6.4hr	0.9–60
J082157.5−430017	Pup A	1–3	1.6–3.3	...	4.5
J121000.8−522628	G296.5+10.0	3–20	1.3–3.9	424ms	2.3
J185238.6+004020(n)	Kes 79	∼9	∼10	...	0.2
J171328.4−394955(n)	G347.3−0.5	∼10	∼6	...	2.8
J000256 +62465 (n,x)	G117.9+0.6[?]	?	∼ 3[?]	...	0.1

Table 1. Compact Central Objects in supernova remnants.

J1617–5102: This central object in RCW 103 was the first radio-quiet X-ray point source found in a young SNR (Tuohy & Garmire 1980). X-ray observations have shown that its flux varies up to 2 orders of magnitude (Gotthelf, Petre & Hwang 1997). First *Chandra* observation showed a modulation of the light curve with about 6 hr period, also found in the *ASCA* data (Garmire et al. 2000). In the second *Chandra* observation the source flux had increased by a factor of 60. The source has been monitored with *Chandra* ACIS, including a 50 ks observation in Continuous Clocking (CC) mode which clearly showed a 6.4 hr period and multiple dips (Sanwal et al. 2002a). The spectrum can be described by an absorbed BB, with temperatures in a 0.4–0.6 keV range, anticorrelated with the flux. The size of the emitting region varied from 0.2 to 1.6 km. The flux variability, the 6.4 hr period, and the dips in the X-ray light curve suggest that this is *an accreting object in a binary system.* We observed the field of RCW 103 CCO in near-IR with VLT and *HST*/NICMOS and found 3 counterpart candidates within the $0\farcs7$ Chandra error circle. The faintness of these objects (e.g., H=22–23) shows that the putative secondary companion is a dwarf of a very late spectral type (later than M4). Therefore, this source is likely an unusual accreting binary, the second known binary in a SNR (after SS 443) and the first LMXB in a SNR. Since the other CCOs show no evidence of accretion, we exclude this source from the CCO list.

J0002+6245: This soft X-ray point source near the CTB 1 SNR, with a possible period of 242 ms, was discovered by Hailey & Craig (1995). The *ROSAT* observation showed a hint on a shell near CTB 1 which could be a new SNR, G117.9+0.6, associated with this point source. This source has been recently observed with *XMM* for 30 ks (Koptsevich et al. 2003). Very strong background flares left large parts of this observation unusable. The spectrum is best fit by a two-component model, a soft BB with a temperature of 0.11 keV and a hard component, either a BB with temperature of 0.5 keV or a PL with photon index of 2.6. The 242 ms period is excluded by the *XMM* observation, and no other

periodicity is found. No SNR around the source is seen in the *XMM* images. The spectral parameters and a lack of a SNR suggest that the point source is a middle-aged pulsar rather than a CCO.

Object	kT keV	R km	$L_{\mathrm{bol},33}$	Γ	$L_{\mathrm{pl},33}$	$n_{\mathrm{H},22}$	$F^{\mathrm{bb}}/F^{\mathrm{pl}}$
J2323+5848	0.43	0.6	1.6	4.2	13	1.8	1.1
	0.43	0.7	1.9	2.5	0.2	[1.2]	4.5
J0852–4617	0.40	0.3	0.3	unconstr	...	0.4	...
J0821–4300	0.40	1.0	3.3	unconstr	...	0.3	...
J1210–5226	0.22	2.0	1.2	3.6	1.2	0.13	3.0
J1852+0040	0.50	1.0	8.0	unconstr	...	1.5	...
J1713–3949	0.38	2.4	15	3.9	72	0.8	0.9

Table 2. Best-fit parameters for BB+PL fits to the *Chandra* spectra.

The spectral parameters for the remaining six CCOs, obtained from fits to *Chandra* ACIS spectra, are listed in Table 2 for the two-component BB+PL model, which became a standard description for INS spectra. The bolometric luminosities L_{bol} for the BB components, and the luminosities L_{pl} for the PL components (in the 0.4–8 keV band), are in units of 10^{33} erg s^{-1}. The hydrogen column densities are in units of 10^{22} cm^{-2}. Significant contributions to the spectra are given by thermal-like emission, with BB temperatures 0.2–0.5 keV and BB radii 0.3–2.4 km, smaller than the expected NS radii, $R_{\mathrm{NS}} = 10$–15 km. Fits with the light-element (H or He) atmosphere models (Pavlov et al. 1995) give lower temperatures, by a factor of ~ 2, and larger radii, by a factor of 2–7, but still the radii remain $< R_{\mathrm{NS}}$ for at least two CCOs (see P02). The PL component is unconstrained in at least some of the fits, which means that either the corresponding spectra are purely thermal or the PL component is too faint to be detected in these observations. Fits with the one-component PL model yield very steep slopes, $\Gamma \sim 5$ (see P02), and they are statistically unacceptable in the cases when many source counts were collected. Since the atmosphere spectra are harder than the BB spectra in the X-ray band, the PL components are, as a rule, unconstrained in the atmosphere+PL fits. Among the six CCOs, only one, J1210–5226, clearly shows spectral lines (see below) while the others are satisfactorily described by featureless continua. The J1210–5226 is also the only CCO for which a period has been detected. None of the six CCOs has shown any long-term variability.

3. Individual Sources

Here we describe the properties of the individual CCOs, with main emphasis on the new results obtained in the last two years. More details about the previous results and the references to earlier works can be found in P02.

Cas A CCO: This prototype CCO has been observed many times with *Chandra* since its discovery in the first-light *Chandra* observation (Tananbaum 1999). We have analyzed the archival *Chandra* observations to search for periodicity, look for long-term variability, and determine its spectral properties (Teter et al. 2003, in preparation). We searched for a period of the point source using

two 50 ks HRC observations (Dec 1999 and Oct 2000) and two 50 ks ACIS observations (Jan 2000 and Feb 2002). No significant periods were found between 0.01 and 100 Hz. To search for long-term variability, we additionally used the calibration observations done every 6 months (typical exposures 1–3 ks) and found no statistically significant variations. The lack of variability during 4 years of *Chandra* observations suggests that it is *not an accreting object* (hence *not a black hole*).

Spectral analysis was performed using the two 50 ks ACIS-S observations and the 70 ks HETG/ACIS observation of May 2001. We find that the BB model gives a better fit than the PL model, with $kT = 0.46 \pm 0.01$ keV and $R = 0.58 \pm 0.03$ km. The two-component models (BB+PL and BB+BB) provide significant improvements over the BB fit, with the soft-BB temperature (0.43 ± 0.02 and 0.37 ± 0.03 keV) and radius (0.6 ± 0.1 and 0.8 ± 0.1 km) similar to those obtained from the single-component BB fit. The photon index of the PL component is strongly correlated with the $n_{\rm H}$ value: $\Gamma = 4.2 \pm 0.2$, $n_{\rm H,22} = 1.8 \pm 0.1$ if $n_{\rm H}$ is a free parameter, while $\Gamma = 2.5 \pm 0.3$ for a more realistic (fixed) $n_{\rm H,22} = 1.2$. The hard-BB component has a temperature of 0.6 ± 0.1 keV and a radius of 0.2 ± 0.1 km, corresponding to $n_{\rm H,22} = 1.2 \pm 0.1$. Substituting H atmosphere models for the thermal emission gives somewhat better fits, with lower temperatures and larger radii (e.g., 0.33 ± 0.01 keV and 2.2 ± 0.2 km for a single-component low-field H atmosphere model), but the radii are still well below $R_{\rm NS}$. The parameters of the hard component in two-component fits are not very sensitive to the choice of soft component model and are less constrained when the H atmosphere models are used. Overall, we conclude that the mostly thermal radiation of the Cas A CCO is emitted from a small, hot area ($R < 2$ km, $kT > 0.3$ keV), perhaps a hot spot on the NS surface, and it is not associated with accretion.

CCO in "Vela Junior": The SNR G266.1–1.2 was discovered by Aschenbach (1998) in the south-east corner of the Vela SNR in the RASS data. An imaging observation with *Chandra* allowed Pavlov et al. (2001) to detect a point source $4'$ from the SNR center and measure its position. The limiting optical magnitude B>22.5 gives high enough X-ray-to-optical flux ratio to believe that this source is a NS, possibly the remnant of the SN explosion. The spectrum of the source was measured by Kargaltsev et al. (2002) from a 30 ks *Chandra* ACIS observation in the CC mode. The PL model does not fit, while the BB model fits very well, giving $kT \simeq 0.4$ keV and $R \simeq 0.3$ km, assuming a distance of 1 kpc. No significant pulsations are found from these data. A 25 ks *XMM* observation (Becker & Aschenbach 2002) gave very similar parameters for the thermal-like radiation and a poorly constrained PL component ($\Gamma = 2.85 \pm 1.0$, $F^{\rm pl}/F^{\rm bb} \approx 0.15$ in the 0.5–10 keV band). Based on the observed properties, we conclude that this source is of the same nature as the Cas A CCO.

Pup A CCO: J0821−4300, located about $6'$ from the center of Puppis A, was discovered with *Einstein* (Petre et al. 1982) and studied with *ROSAT*, *ASCA*, *Chandra* and *XMM*. Its X-ray spectrum is very similar to those of the Cas A and Vela Junior CCOs. The spectrum observed with *Chandra* fits well with one-component thermal (BB or light-element atmosphere) models (P02), while fitting the *XMM* spectrum requires an additional hard component (PL with $\Gamma = 2.0$–2.7 or hard BB with $kT = 0.5$–1.1 keV — Becker & Aschenbach 2002). This CCO has a larger size of the emitting region ($R \sim 1$ km and ~ 10 km

for the BB and magnetic H atmosphere models, respectively). Observations with *Chandra* HRC have shown no PWN and no significant periodicity in the 0.003–300 s range (P02).

CCO in PKS 1209–51/52: J1210−5226 (a.k.a. 1E 1207.4–5209) was discovered by Helfand & Becker (1984). It is located about $6'$ off the center of PKS 1209–51/52 (G296.5+10), at a distance of about 2 kpc. This source has been observed with all the X-ray observatories since *Einstein* (see P02 for references). The low-resolution spectra obtained in the pre-*Chandra* era can be described by thermal continuum models; e.g, the BB fits give $kT \simeq 0.25$ keV and $R \simeq 1.6$ km. Fits with magnetic NS atmosphere models show a lower temperature and a size compatible with that of a NS (Zavlin et al. 1998).

Two *Chandra* observation of this source resulted in the discovery of a period of 424 ms (Zavlin et al. 2000) and a surprisingly small period derivative, corresponding to a characteristic pulsar age of ~ 500 kyr (vs. 3–20 kyr for the SNR) and magnetic field $\sim 3 \times 10^{12}$ G (Pavlov et al. 2002b). Spectral fits to the *Chandra* data show two broad absorption lines, near 0.7 and 1.4 keV (Sanwal et al. 2002b), the first lines detected in an INS spectrum. Further observations of this source with *XMM* have shown that there might be additional absorption lines near 2.1 and 2.8 keV (Bignami et al. 2003). The origin of the lines is not clear at present.

We found no long-term flux variations, neither between different observations nor within long separate observations, which suggests that the X-ray radiation is *not* associated with accretion. On the other hand, timing analysis of the *Chandra* and *XMM* observations have allowed us to discover apparent deviations from uniform spin-down, suggesting that the CCO could be in a wide binary system, with $P_{\rm orb} \sim 0.2$–6 yrs (Zavlin et al. 2003). We observed the field with VLT and *HST*/ACS and found a faint, red object (V$\simeq$26.4, K$_s$ $\simeq$20.7) in the $1''$ *Chandra* error circle, whose spectrum suggests an M4 or M5 dwarf (Moody et al. 2003, in preparation). If this is the CCO optical counterpart, then it would be the second LMXB (but not a usual one!) in a SNR, after the central source in RCW 103.

Thus, we see that J1210–5226, the coldest (the oldest?) among the six CCOs, is the only one showing spectral lines (but none of the others was observed for so long time), the only one for which a period was detected (albeit with a puzzling time dependence), and the only one that might be in a (non-accreting) binary. Solving the riddles exhibited by this best-studied CCO may give a clue to understanding the nature of the enigmatic CCO family, unless this "outstanding CCO" is a truly unique object.

CCO in Kes 79: Kes 79 (G33.6+0.1) is a shell-like SNR (diameter $\sim 11'$) at a distance of 10 ± 2 kpc, with an age of 6–12 kyr (Seward & Velusamy 1995). It has been observed in X-rays with *Einstein*, *ROSAT*, and *ASCA*. *Chandra* ACIS observation of Kes 79 (Seward et al. 2003) showed a point-like source at its center. Since neither PWN nor optical/radio counterparts have been detected, this source is a viable CCO candidate. The upper limit on pulsed fraction is about 30%, for periods longer than 6.4 s. The spectrum of this putative old CCO is thermal-like, its BB temperature, 0.48 keV, being even higher than that of the youngest Cas A CCO, is comparable to magnetar temperatures of similar ages.

CCO in G347.3–0.5: G347.3–0.5 is a radio-faint, shell-like SNR with a nonthermal X-ray spectrum, at a distance of about 6 kpc. *ROSAT* PSPC observations of G347.3–0.5 (Pfeffermann & Aschenbach 1996) showed a central point source, for which neither optical/radio counterpart nor X-ray pulsations have been detected (Slane et al. 1999). Results of the *Chandra*, *XMM* and *RXTE* observations of this source have been reported by Lazendic et al. (2003). The combined *Chandra* and *XMM* spectra of the CCO can be reasonably fit with either a single BB ($kT \simeq 0.4$ keV, $R \simeq 2.5$ km) or a steep PL ($\Gamma \simeq 4.2$). The best fit to the CCO spectrum is given by a BB+PL model, with $kT = 0.38$ keV and $\Gamma = 3.9$, similar to other CCOs where the two-component model fits are constrained.

4. Evolution and H-R diagram for CCOs and Magnetars

The above-described spectral observations of CCOs make it possible to examine the age dependence of the spectral parameters. Figure 1 shows such dependences for the BB temperature and radius. Since the observed CCO spectra are similar to those of magnetars in quiescence, we added the data on a few AXPs and SGRs (from Mereghetti et al. 2002). We see from Figure 1 that CCOs,

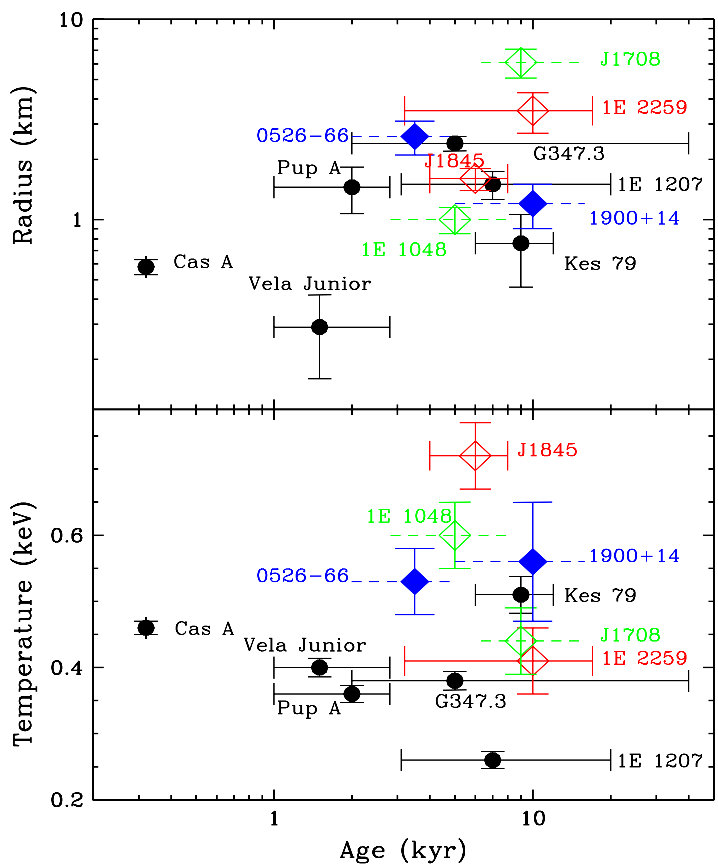

Figure 1. Age dependences of BB radius and BB effective temperature for CCOs (filled circles), AXPs (open diamonds) and SGRs (filled diamonds). For objects with known SNR association, estimated SNR ages are used (solid horizontal error-bars) while for four magnetars (marked with horizontal dash lines) we use spin-down ages.

being on average younger than magnetars, have somewhat lower temperatures and smaller sizes, albeit with significant overlaps. Interestingly, the overlap in the temperature-age diagram disappears if the Kes 79 CCO is attributed to the magnetar group. In this case the five CCOs lie along a “cooling branch”, while

the magnetars show no temperature-age correlation. If we consider CCOs and magnetars as a single group, no significant temperature-age correlation is seen. On the other hand, the effective radii of CCOs and magnetars do show positive correlation with age (a hot spot spreads over the NS surface? a hole in a 'screen' gets bigger?), with magnetars being on average older than CCOs. In the luminosity-temperature diagram (an analog of Hertzsprung-Russell diagram — Fig. 2) the CCO and magnetar populations almost do not overlap (magnetars are hotter and more luminous), lying on the same 'sequence'.

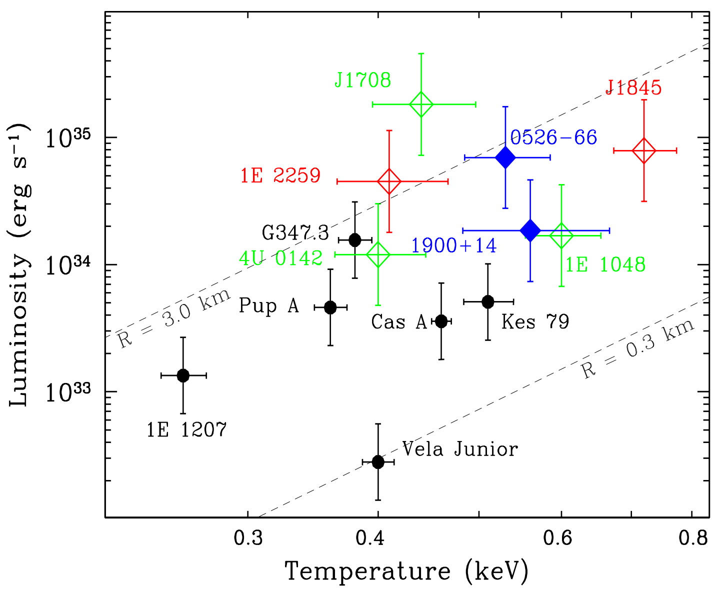

Figure 2. The dependence of bolometric BB luminosity on BB temperature (Hertzsprung-Russell diagram) for CCOs and magnetars. The lines of constant BB radius are plotted at 0.3 km and 3.0 km.

Thus, at least some CCOs appear to be relatives of AXPs and SGRs, but their relationship is not fully understood. On average, CCOs are younger, perhaps colder, and their emitting areas are smaller than those of AXPs and SGRs. Does it mean that CCOs are actually young magnetars, not mature enough to develop characteristic properties of AXPs/SGRs (e.g., they have not spun down to the 5–12 s period range, or their crusts are still too durable to crack and cause bursts)? This hypothesis could, at least, explain the lack of pulsar activity in CCOs, but it seems to be at odds with the properties of 1E 1207.4–5259, the best-studied CCO (unless it is a different kind of object).

To conclude, we now have strong reasons to believe that CCOs are not black holes, and their radiation is not powered by accretion. Very likely, they are isolated "neutron stars" (perhaps composed of more exotic particles, e.g., quarks), but at least most of them are not ordinary rotation-powered pulsars. Apparently, their thermal-like X-ray emission emerges from a part of NS surface. We can speculate that the internal heat of the NS is somehow channeled into these small areas (e.g., by superstrong localized magnetic fields) or most of the surface is covered by a thermo-isolating "blanket" or a "screen" opaque for soft X-rays. Alternatively, the hot spots could be heated by some local sources (dissipation of superstrong magnetic fields? nuclear reactions?). Future X-ray timing and spectral observations, together with deep NIR imaging, are needed to understand the true nature of CCOs.

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